Department of Energy
Germantown, MD 20874-1290

SAFETY EVALUATION REPORT

Mark 15 and FERMCO Product Ingots in the Rev. 0 SARP of the Steel Banded Wooden Shipping Containers (SBWSC)

Docket No. 01-05-5467

Background

The criticality confirmatory evaluation in this Safety Evaluation Report (SER) addresses the Mark 15 Ingots (Outer and Inner) and the FERMCO Product Ingots as described in the Rev. 0 SARP for the Steel Banded Wooden Shipping Containers (SBWSC). The Mark 15 Ingots and the FERMCO product Ingots are unirradiated, low enrichment (1.106 and 1.256 wt.% U-235 max., respectively) annular cylindrical ingots with lengths varying between 12 and 29 inches. The SARP proposes to ship the Mark 15 Ingots and the FERMCO Product Ingots in the SBWSC Models G-4273-5 and G-4273-6, respectively, in an exclusive use shipment.

The staff reviewed the criticality analyses presented in the Rev. 0 SARP and performed independent confirmatory evaluation of criticality safety for the Mark 15 Ingots and the FERMCO Product Ingots. The staff confirmed that the Transport Index (TI) and the number of packages, listed in Table 1.2.3-2 of the SARP and Table 1 of this SER, for shipping the Mark 15 Ingots (Outer and Inner) and the FERMCO Product Ingots, in an exclusive use shipment, meet the criticality safety requirements of 10 CFR 71 under normal conditions of transport (NCT) and hypothetical accident conditions (HAC).

Other safety aspects (i.e., general information, structural, thermal, shielding, containment, operating procedures, acceptance tests and maintenance, and quality assurance) of the SBWSC have been reviewed for similar types of payloads in the Rev. G through Rev. L of the SARP and documented in the SERs for Rev. 11 through Rev. 20 of the Certificate of Compliance (CoC). The conclusions obtained in the earlier evaluation and SERs for the other safety aspects of the SBWSC remain valid and applicable to the payloads evaluated in this SER and will not be repeated.

Criticality Safety Evaluation

No special feature is incorporated in the design of the SBWSC for criticality control. According to 10 CFR 71, criticality safety must be demonstrated for a fissile material package under NCT and HAC. The hypothetical accidents consist of a sequence of events (e.g., vertical drops, fire, and immersion in water) that would damage the package and thus often represent a more limiting condition for criticality safety analysis, i.e., 2xN damaged array analysis where N is the number of packages in the array according to 10 CFR 71.59. In the criticality analysis for the SBWSC, the applicant conservatively assumed that all SBWSC in a shipment are burned during the 30-minute hypothetical accident fire (even though the wooden boxes are most likely only charred), and that the ingots are "scattered and arranged" in the most reactive configuration with optimal interspersed hydrogenous moderation and total water (30 cm) reflection, as required by 10 CFR 71.55 and 10 CFR 71.59. The staff confirmed that the applicant has used the appropriate lengths of the ingots to establish the “maximum subcritical mass” for each payload type consisting of the Mark 15 Outer Ingots, Mark 15 Inner Ingots, and FERMCO Product Ingots. The staff also confirmed that the applicant has indeed established the most reactive configuration for the number of ingots (and packages) allowed in a shipment that would remain subcritical with an adequate safety margin.

Determination of Optimal Lattice Parameters and the Most Reactive Configuration

Determination of the maximum allowable number of uranium ingots under the most reactive configuration begins with a search for the optimal lattice parameters, i.e., pitch, axial gap, and moderator density, that would maximize the neutron multiplication factor (k_∞) for an infinite array of ingots in a close-packed, hexagonal lattice. The staff found that for a given uranium ingot composition and geometry, the k_∞ is mainly influenced by the amount of water in the unit cell for the hexagonal lattice configuration. Consequently, a loosely packed array with a relatively large pitch and axial gap and low moderator density can have a mass ratio of fissile to moderator material similar to that of a tightly packed array with a smaller pitch and axial gap, but higher moderator density. Infinite arrays of ingots having these two types of lattice parameters will have comparable k_∞ values, and thus can be regarded as equally reactive configurations. Determination of the most reactive configuration, therefore, must consider the effect of neutron leakage, which exists only for a finite array of ingots.

Since neutron leakage from a system reduces reactivity, the most reactive configuration for a finite array of ingots must be one with a minimum surface-to-volume ratio that gives the smallest total surface area for neutron leakage. A tightly packed array within a spherical enclosure and with total water reflection, therefore, should minimize neutron leakage. The staff has developed the necessary framework for determining the radius of the spherical enclosure for the finite array using iterative MCNP calculations (See "Criticality Control in Shipments of Fissile Material," J. R. Liaw and Y. Y. Liu, Proc. ANS Topical Meeting on Spent Fuel and Fissile Material Management, San Diego, CA., June 5-8, 2000, pp. 347-352). The most reactive configuration of the finite array (and the maximum number of ingots allowed in a shipment) is determined when the adjusted effective neutron multiplication factor (k_{adj}) for the 2xN damaged array satisfies the following criterion,

$$k_{adj} = k_{eff} + 0.00258 + 2 \times (0.006^2 + \sigma^2)^{0.5} < 0.95,$$

where k_{eff} and σ are the effective neutron multiplication factor and uncertainty, respectively, obtained in the MCNP calculations. The other constants in the equation are the code bias (0.00258) and uncertainty (0.006) obtained from benchmark calculations against the critical experiments. This is the same formula used by the applicant in the SARP, and the formula is consistent with that recommended in NUREG/CR-5661, "Recommendations for Preparing the Criticality Safety Evaluation of Transportation Packages," April 1997.

Determination of Transport Index and Maximum Number of Packages per Shipment

The applicant followed the above procedure and determined the radius of spherical enclosure for the 2xN damaged arrays of the Mark 15 Outer Ingots (29 in. L), the Mark 15 Inner Ingots (19 in. L), and the FERMCO Product Ingots (12 in. L, minimum length), respectively. The amount of fissile material within the spherical enclosure is the "maximum subcritical mass" determined and listed in the SARP [(10,984 kg in Table 6.4.3-4(C), 10,984 kg in Table 6.4.3-3(C), and 25,120 kg in Table 6.4.3-10(D)] that corresponds to the above ingot types and lengths, respectively. It has been shown by the applicant and confirmed by the staff reviewer that the "maximum subcritical mass" of a given ingot length (e.g., FERMCO Product Ingots of 12 in. minimum length) can be used to establish the minimum Transport Index for similar ingots of the same inner and outer diameters but longer lengths (e.g., FERMCO Product Ingots of 17 in. L). This rule is conservative because fissile material of the same composition and total mass is generally more reactive in smaller physical dimensions. The mass for the Mark 15 Outer and Inner Ingots are 501.2 kg and 277.4 kg, respectively. The mass for the FERMCO Product Ingots with 12 in. L or 17 in. L are 474.6 kg or 672.3 kg, respectively.

For the Mark 15 Ingots, the applicant determined the allowable number of packages per shipment (2xN) by dividing the "maximum subcritical mass" by the amount of uranium per package (number of ingots per package x the mass of the ingot) for each payload type. By definition, the TI for criticality control is TI = 50/N, and the sum of TI of all packages should be less than 100 in an exclusive-use shipment. For example, the total number of 2xN damaged packages for the Mark 15 Inner Ingots is determined from its maximum subcritical mass (10,984 kg) divided by the product of the mass of the Mark 15 Inner Ingot (277.4 kg) and the number of the Mark 15 Inner Ingots per package (4), i.e., 2xN = 10,984/(277.4 x 4) = 9.9; hence N = 4.95. The corresponding transport index (TI) for criticality control is calculated from TI = 50/N = 50/4.95 = 10.101 which is rounded up to 10.2. The same procedure is used to calculate the TI value for the Mark 15 Outer Ingots shown in Table 1.

For the FERMCO Product Ingots with lengths varying from 12 to 17 in. L, the applicant determined the "maximum subcritical mass" to be 25,120 kg based on the minimum length of 12 inches as shown in Table 6.4.3-10(D) of the Rev. 0 SARP. The corresponding k_{adj} value, obtained by the applicant and independently confirmed by the staff reviewer as shown in Table 1, meets the subcriticality criterion of 0.95 with adequate safety margin. Although not stated explicitly in Chapter 6 or Chapter 1, Table 1.2.3-2 of the Rev. 0 SARP listed only 2 FERMCO Product Ingots (lengths vary between 12 and 17 in.) per package and a total of 13 packages per exclusive use shipment. Even for the longest (17 in. L) FERMCO Product Ingots, such a loading configuration is acceptable since it does not violate the "maximum subcritical mass" limit of 25,120 kg, nor exceed the package weight limit of 3,488 lb for the SBWSC Model G-4273-6. Using a minimum TI = 7.6 for the FERMCO Product Ingots with lengths varying from 12 to 17 in. thus satisfies the 42,000 lb weight limit and is conservatively criticality safe in an exclusive use shipment.

Table 1 summarizes the minimum TI values and other pertinent information for each payload type evaluated in this SER. The last two columns in Table 1 give the k_{adj} values from the SARP and the staff's independent confirmatory analysis (labeled as SER) for the specified payload types. Based on the results in Table 1, the staff has thus independently confirmed that the k_{adj} values for shipping each of the payload types in their corresponding designated SBWSC Model meet the subcriticality criterion of 0.95 with adequate safety margin.

Table 1. Transport Index (TI) for Criticality Control for the Mark 15 Ingots (Outer and Inner) and the FERMCO Product Ingots in the SBWSC (Rev. 0 SARP)

Payload ID/OD x L (in.)	SBWSC Model	Ingots/ Package	Packages/ Shipment	Min. TI	k_{adj}	
					SARP	SER
Mark 15 Outer 3.19/9.0 x 29	G-4273-5	2	10	9.2	0.9340	0.93088
Mark 15 Inner 2.04/8.0 x 19	G-4273-5	4	9	10.2	0.9386	0.93864
FERMCO Product Ingots 2.87/13.05 x 12-17	G-4273-6	2	13	7.6[a]	0.9431	0.94399

[a] Loading is based on 2 ingots per package as listed in Table 1.2.3-2 of the Rev. 0 SARP. The minimum TI (7.6) and the maximum number of packages per shipment (13) are based on the maximum weight limit of 42,000 lbs. for the payload. Confirmatory TI differs from that in Rev. 0 of the SARP.

Summary

The staff has evaluated the criticality safety analyses presented in the Rev. 0 SARP for the Mark 15 Ingots (Outer and Inner) and the FERMCO Product Ingots. The staff has performed independent calculations and confirmed that the minimum TI values (and the corresponding maximum number of packages) for the Mark 15 Ingots (Outer and Inner) and the FERMCO Product Ingots listed in the Rev. 0 SARP and Table 1 of this SER are conservative and meet the 10 CFR 71 requirements under NCT and HAC.

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